# Differential Radial Velocities and Stellar Parameters of Nearby Young Stars

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## ABSTRACT

Radial velocity searches for substellar mass companions have focused primarily on stars older than 1 Gyr. Increased levels of stellar activity in young stars hinders the detection of solar system analogs and therefore there has been a prejudice against inclusion of young stars in radial velocity surveys until recently. Adaptive optics surveys of young stars have given us insight into the multiplicity of young stars but only for massive, distant companions. Understanding the limit of the radial velocity technique, restricted to high-mass, close-orbiting planets and brown dwarfs, we began a survey of young stars of various ages. While the number of stars needed to carry out full analysis of the problems of planetary and brown dwarf population and evolution is large, the beginning of such a sample is included here. We report on 61 young stars ranging in age from $\beta$ Pic association ($\sim$12 Myr) to the Ursa Majoris association ($\sim$300 Myr). This initial search resulted in no stars showing evidence for companions greater than $\sim$1-2 $M_{Jup}$ in short period orbits at the $3\sigma$-level. Additionally, we present derived stellar parameters, as most have unpublished values. The chemical homogeneity of a cluster, and presumably of an association, may help to constrain true membership. As such, we present [Fe/H] abundances for the stars in our sample.

*Subject headings:* stars: planetary systems — techniques: radial velocities — stars: activity— clusters: IC 2391, $\beta$ Pic, Castor, Ursa Majoris — stars: abundances

## 1. Introduction

The primary drive in extrasolar planet and brown dwarf detection is to determine whether our solar system is unique and how our solar system formed and evolved into its present stablity. Currently, radial velocity surveys probe nearby, solar-like stars for planets and brown dwarfs. As new space-based missions (e.g., Kepler, Gaia, SIM, TPF, and Darwin) are launched, the question to be answered is whether habitable planets exist outside of our solar system. Precursor studies, like radial velocity and transit surveys, to these missions must seek to understand the nearby stellar systems that will be targets for these missions.

Focusing on solar-type stars, however, sidesteps the issues regarding the formation and evolution of planets and brown dwarfs. To understand these issues, we must survey young stars for substellar mass companions. With the advance of adaptive optics and interferometric imaging, various groups (e.g., Neuhäuser et al. 2003; Kaisler et al. 2003; Masciadri et al. 2005; Lowrance et al. 2005; Zuckerman et al. 2001) have begun to do just this.

These surveys are building reasonable statistics of substellar mass companions around the youngest stars. It is important to note that imaging surveys are most sensitive to young, massive and distant companions (Brandner & Kasper 2005). As technology progresses, these instruments will be able to reach lower masses with increased sensitivity and with increased resolution, they will be able to probe the inner few AU of nearby stars. The closest companions (orbits of a few days - months) are unlikely to be detectable with direct imaging anytime in the forseeable future.

The radial velocity method for detecting extrasolar planets is widely successful, having been used to detect over 150 planets to date (Marcy et al. 2005). Unfortunately, the technique is subject to significant limitations. The method relies on measuring the average line center for hundreds - thousands of stellar and reference lines in order to achieve the 2-3 m $s^{-1}$ precision required to detect low mass planets around nearby stars. Anything that causes temporal changes in the line profiles, including but not limited to strog magnetic fields, will adversely affect this measurement and hence the radial velocity precision, as is discussed by Saar & Donahue (1997) and Hatzes (2002). Hatzes (2002), Saar & Donahue (1997) and Wright (2005) discuss the details of this issue and estimate the amplitude of this effect for various types of stars. We must weigh the benefits of the radial velocity technique with the pitfalls. The amplitude of the radial velocity perturbations induced by a close orbiting high mass companion can be up to a few km $s^{-1}$. The intrinsic noise caused by stellar activity is typically less than 0.15 km $s^{-1}$ for stars older than ∼50 Myr (§4.1). Thus, high mass short period companions can be detected in a straightforward fashion using the radial velocity method, and this is the focus of this paper[1]. It may be possible to remove the effects of stellar activity from radial velocity measurements (e.g., Martínez Fiorenzano et al. 2005; Saar et al. 2003) in order to search for lower mass companions, but we do not attempt such a feat.

[1]We also would like to note the simultaneous efforts of Esposito et al. (2005) in carrying out a similar radial velocity search for extrasolar planets around young stars.

## 2. Sample

For this study, stars were chosen in different age groups while a larger sample of "other" nearby young stars was also included. The ages of stellar groups and associations range from the 12 Myr old $\beta$ Pic association (Zuckerman et al. 2001) through the Ursa Majoris association, estimated to be ∼300 Myr (Soderblom & Mayor 1993).

The $\beta$ Pic association has gained much attention (e.g., Zuckerman et al. 2001; Song et al. 2003; Ortega et al. 2004) in the past few years because the members are at an interesting age, ∼12 Myr, roughly the age of circumstellar dust clearing. This is the youngest group of stars in our survey and thus has significantly more intrinsic activity than any other star in this survey. For these members, planetary mass companions are unlikely to be detected. However, binary and brown dwarf multiplicity is important for models of star formation in stellar associations. It is for these reasons that imaging surveys of $\beta$ Pic members have been undertaken (e.g., Zuckerman et al. 2001; Neuhäuser et al. 2003). Abundance analysis of these stars likely requires incorporation of non-LTE model atmospheres and such an analysis is not undertaken here.

IC 2391 is a cluster of age ∼30-50 Myr (Mermilliod 1981; Barrado y Navascués et al. 2004; Patten & Simon 1996) at a distance of ∼150 pc (Dodd 2004; Stauffer et al. 1989). There are possibly as many as 125 members of IC 2391 (Dodd 2004). We present analysis of only seven of these members. IC 2391 represents an excellent proving ground for studies of stellar activity (e.g., Marino et al. 2005; Simon & Patten 1998) and angular momentum evolution (e.g., Patten & Simon 1996; Stauffer et al. 1997) because the stars are coeval, presumably of similar initial stellar composition and have ages between the youngest stars and the older clusters (such as the Pleiades). Randich et al. (2001) find $\log\epsilon(\mathrm{Fe})=7.49$ for this cluster, placing it just supersolar in metallicity (assuming $\log\epsilon(\mathrm{Fe})_{\odot}=7.45$, Asplund, Grevesse & Sauval 2005).

Anosova & Orlov (1991) first suggested the existence of the Castor moving group as an association of 15 stars. Barrado y Navascues (1998) revisited this group of stars, adding additional "probable" members of the group, and determined an

age of 200±100 Myr. Members were then added by Montes et al. (2001). From these surveys, we chose seven stars. Metallicity determination for this moving group has not yet been explored in detail and our derived metallicities help constrain membership in this moving group.

The oldest association of stars we consider is the Ursa Majoris moving group. Member stars are ∼300 Myr (Soderblom et al. 1993). They are a kinematically classified group of stars with, presumably, homogeneous origins. Membership of this association has been carefully studied over the past several years (see, for example Soderblom & Mayor 1993 and Montes et al. 2001). Twelve stars are included in this study. These stars are also suited for more precise radial velocity measurements for companion detection because by this age, the stars are less active. The coarse radial velocity precision resulting from the use of telluric lines dominates the measurement error. There are few nearby, bright stellar associations, so this becomes an important group for studies rearding chemical evolution. The metallicity has been measured to be -0.09 (Boesgaard & Friel 1990) and -0.05 (King & Schuler 2005). King & Schuler (2005) further discuss the large scatter in abundances of their sample of seven members and the possibility for initial chemical inhomogeneity. They also provide a nice tabulation of the abundances for several other Ursa Majoris members from the literature.

Stars for our sample were chosen from two published surveys of nearby young stars Montes et al. (2001) and Zuckerman et al. (2001). For stars taken from Montes et al. (2001), the star must have met the criterion that the space velocity (U, V, W) agrees with a convergent point method for the group and at least one of the Eggen's kinematic criteria: peculiar or radial velocity, but not necessarily both.

We can also place possible constraints on membership according to measured stellar abundance. Stellar clusters are formed from the same material and as such should have the same initial stellar composition. And, indeed, older clusters have remarkable consistency in [Fe/H], (e.g. Paulson et al. 2003). Large deviations in stellar composition may indicate either pollution of the stellar photosphere or protostellar nebulae of unequal composition. Because of the ambiguity, we can only offer a new label of "possible non-member". Discrepancies of stellar abundance with respect to cluster or association mean have been pointed out in each of the Results sections.

A further restriction was placed on the rotational velocity of the star. The higher mass stars (earlier than F8) have higher rotation rates which broaden the stellar lines and reduce the velocity precision. Typically radial velocity surveys which employ the $I_2$ cell place a 10-15 km s$^{-1}$ cutoff for maximum stellar $v\sin i$, giving preference to stars with much lower $v\sin i$. Because we are not attempting to achieve 3 m s$^{-1}$ precision, this constraint was relaxed to ∼20 km s$^{-1}$.

## 3. Observations

The observing program was designed to maximize efficiency and this project lends itself well to quick detection of high mass, close-in companions. The goal was to survey about two dozen stars during a 3-4 night run by taking 2-4 spectra of each star each night. During the next run, stars from the previous runs that showed large amplitude variability over a few day's time were reobserved. In this way, more than a dozen stars were eliminated as having no close-in, high-mass companion and did not need to be reobserved. We surveyed a total of 61 stars.

Of the nights granted for this project on the Magellan telescopes, data were collected on the nights listed in Table 1. The MIKE spectrograph (Bernstein et al. 2003) was used with the 0.35" slit, yielding a resolving power of ∼54,000 on the red chip and ∼70,000 on the blue chip. The red grating angle was offset twice during the course of these observations, and in Table 1 we list the wavelength ranges for each observing run. The blue chip went unchanged throughout the course of this investigation. No noticeable offset was observed between shifts of the spectrograph to within errors of our technique. Observations were only recorded when seeing was sub-2". Exposures were constrained to 30 minutes or less to maximize velocity precision, with typical exposures ranging from 2-15 minutes.

Spectra were reduced using standard IRAF[2] packages. After flat fielding and removal of the

[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of

bias with the ccdproc routine, we used a suite of IRAF routines, mtools, for use in specifically handling MIKE spectra. The mtools routines were developed by J. Baldwin and are publicly available at the Las Campanas Observatory website (www.lco.cl). MIKE spectra have a tilt of the slit with respect to the orders (Bernstein et al. 2003). The mtools routines calculate the varying slope of the tilt using ThAr calibration spectra along the orders and across each chip. It is repeated for each of the ThAr spectra taken throughout the night. The tilt is then removed from all spectra during the extraction of the spectral orders. Once the spectra have been corrected for the tilt, a wavelength solution is applied using the IRAF package ecid.

In lieu of an $I_2$ cell, we took advantage of the telluric oxygen band at 6900Å for our velocity reference. Our philosophy in not using the $I_2$ cell was that the intrinsic noise of these objects will exceed the few m $s^{-1}$ precision one can achieve with the cell. Longer term projects, investigating either the intrinsic and variable activity of the stars or the presence of longer period high mass companions, would benefit from the use of an $I_2$ cell.

## 4. Analysis

### 4.1. Radial Velocities and Errors

The MIKE spectrograph is not fiber-fed and thus the measurement of radial velocities to this precision is hindered by guiding errors, however this is not easily corrected for. Variable positioning of the stellar image on the slit illuminates the spectrograph non-uniformly. This variable illumination causes inherent shifts of the stellar absorption features. The use of telluric features as a velocity reference only corrects for part of this error, as the telluric features are themselves broad. Instrumental errors are also introduced by temperature fluctuations in the spectrograph, as it is not in a temperature controlled environment. These are removed by taking frequent ThAr spectra for contemporaneous wavelength solutions. As a check that this was necessary, we measured the relative velocity shifts of the ThAr spectra throughout the night. The maximum variation throughout the course of one observing night was 0.7 km $s^{-1}$. Thus, ThAr spectra were taken between 10 and 20 times each night for wavelength calibration. The wavelength solution nearest in time to the stellar spectrum was applied.

Radial velocities are measured via cross-correlation of each observation with a "template" spectrum of that same star using the IRAF package *fxcor*. The template spectrum was chosen to be the spectrum with the highest signal-to-noise. We subtracted the differential velocity shift of the telluric lines from those of the stellar lines to obtain the final radial velocity for that observation in the heliocentric frame of reference (provided within *fxcor*). The value $A_{obs}$ (in Tables 2, 3, 5, 7 and 9) is the 1-$\sigma$ rms of all velocity measurements for each star. Each observation also includes an associated error. This error is determined by adding in quadrature the cross correlation error derived in *fxcor* for the stellar lines with that of the telluric features. The error listed for each star, $\sigma_{\rm error}$ in the Tables, as well as in Figure 1, is the rms of the errors for all observations of a given star.

Under good seeing conditions (∼0.5") and on bright (V∼8), slowly rotating stars we were able to obtain velocity precision of 0.01 km $s^{-1}$ for an individual observation, with an rms of 0.02-0.03 km $s^{-1}$. Two stars known to not harbor hot Jupiters were observed: $\tau$ Ceti and HD 99109. We chose these to look for systematics during the course of observations, though no systematics were found at our detection threshold. These two stars also provide confirmation of our above quoted errors. $\tau$ Ceti was observed 11 times over 7 nights and exhibited velocity variations $A_{obs}$=0.03 km $s^{-1}$ with $\sigma_{\rm error}$=0.04 km $s^{-1}$. And, HD 99109 which was observed 16 times over 10 nights has $A_{obs}$=0.04 km $s^{-1}$ and $\sigma_{\rm error}$=0.04 km $s^{-1}$. Our somewhat crude velocity precision is sufficient for detection of high mass, close-in planets and brown dwarfs as the velocity variations will exceed the combination of the intrinsic noise caused by stellar activity and the instrumental error (which includes the uncertainties arising from use of telluric features).

We adopt the empirical relationship of Saar & Donahue (1997), using our measured rotational velocities and Hipparcos photometry, to compare observations with predicted radial velocity am-

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plitudes induced by the rotational modulation of starspots. According to the Saar & Donahue relationship, G-type stars of Hyades age (∼650 Myr) will have a maximum predicted radial velocity amplitude of ∼30-40 m $s^{-1}$, while G-type stars of $\beta$ Pic age (∼12 Myr) can exhibit radial velocity variations ∼0.7 km $s^{-1}$. It is apparent that the only detectable companions around the youngest stars will be close-in brown dwarfs and stellar binary companions. Any information on the presence of companions (stellar or otherwise) around these young stars is useful for understanding the dynamics of post-T Tauri systems. For the calculation of predicted maximum amplitudes, $A_{pred}$=$0.6 f_S^{0.9} v\sin i$ (where $f_S$=∼$0.4\Delta$V is given in percent) we make use of our measured $v\sin i$ (§4.3), when available and the Hipparcos photometric database (ESA 1997), unless otherwise noted. The adopted and measured values are listed in Tables 2, 3, 5, 7 and 9. Hipparcos measures magnitudes in a slightly different bandpass as V, but the amplitude of the variability is similar. From the database, we take as the amplitude the difference between the 95% and the 5% photometric levels. We list these values as $\Delta V_H$. Observed versus predicted radial velocity amplitudes, including velocity errors, are shown in Figure 2. A 1:1 line is drawn for reference as well as a (dashed) line representing the mean error for all observations. Two stars have arrows indicating the questionable Hipparcos photometry. The end points of these arrows are the values obtained if we assume photometry taken from ground-based surveys.

### 4.2. Limits on Detectable Companions

Using the methods of Nelson & Angel (1998, hereafter NA98) as we did in Paulson et al. (2004), we determine limits on companions detectable given the data quantity and quality for each star (as listed in the respective tables). The error we assume is the predicted velocity caused by stellar activity, $A_{pred}$, added in quadrature with the mean observational error, $\sigma_{\rm error}$. The value $M_{3\sigma}$ is the lower mass limit of companions (>1$M_{Jup}$) that can be ruled out at the 3-$\sigma$ level in orbits of 6 or fewer days. The number of independent frequencies sampled is given in Eq. 14 of NA98. We have assumed even sampling, but as our data is not uniformly sampled, it is possible to search much higher frequencies than then Nyquist frequency. The velocity that will be exceeded in a given frequency range, $K$, is dependent on the square root of $ln(1/N)$, where $N$ is the number of independent frequencies in a given frequency range (see Eq. 15 in NA98). Thus, a change in the number of independent frequencies by a factor of 2 only results in a fractional change of $K$. And, as such, our assumption of evenly sampled data does not significantly affect the results of this analysis. Upon inspection of the table, the most massive planets and brown dwarfs are ruled out for all stars. For most stars, planets as small as 1 $M_{Jup}$ can also be ruled out. The mass limit of companions around these stars can be decreased with an increased number of observations as well as more precise radial velocities for the less active stars. However, the mass limits for the youngest stars (such as the $\beta$ Pic members) remain limited by the intrinsic activity of the star.

### 4.3. Stellar Parameters and Abundance Analysis

In order to measure rotational velocities, $v\sin i$, for each star, we employ the curve of growth method to determine stellar parameters. These parameters are then used to model a small spectral section to extract line broadening resulting from stellar rotation.

For the majority of stars in this sample, we have derived the stellar parameters and metallicity using the spectral synthesis code MOOG (Sneden 1973), in the same fashion as we did in Paulson et al. (2003). It has been recently shown that cooler stars exhibit an ionization imbalance which increases as the stellar temperature decreases (e.g., Allende Prieto et al. 2004; Yong et al. 2004). Allende Prieto et al. (2004) suggest that this, sometimes severe, departure from LTE stems from an increase in stellar activity (in cooler stars relative to warmer stars with shallower convective regions). If this is indeed the root cause of these discrepancies, then the increase in activity as a result of stellar youth would also imply the requisite use of non-LTE stellar atmopsheres. We did not attempt measurement of stellar parameters for the $\beta$ Pic members and stars cooler than K2 because of this issue. We also note that for some elements, the use of LTE models may result in incorrect abundances for all stars in this survey

because of their youth.

We use stellar atmosphere models based on the (LTE) 1995 version of the ATLAS9 code (Castelli et al. 1997), and while newer non-LTE models have recently become available (e.g. Hauschildt et al. 1999), they require too great of computational time to obtain a reasonably large grid of atmospheres. We have thus adopted $v\sin i$ values from the literature (references are noted in the tables) for those stars for which we have not derived atmospheric parameters.

Within IRAF, EWs are measured by fitting Gaussians to Fe I and Fe II lines (see Table 1 in Paulson, Sneden & Cochran 2003 for the linelist used). The EWs are input into MOOG drivers along with the individual line parameters to back out the effective temperature, $T_{\rm eff}$, surface gravity, $\log g$, microturbulence, $\xi$, metallicity, [Fe/H] and finally, the rotational velocity, $v\sin i$. The $v\sin i$s are measured by spectral synthesis after determining the appropriate stellar atomosphere model, via the curve of growth routine (*lin*), by employing the *synth* feature of MOOG. Our grid of models dictates the errors on $T_{\rm eff}$, $\log g$ and $\xi$ to be 50 K, 0.1 cm s$^{-2}$ and 0.2 km s$^{-1}$, respectively. In order to determine [Fe/H], we require that the $T_{\rm eff}$ be independent of excitation potential for all Fe I lines, and $\xi$ must be independent of line strength. Upon fitting these two parameters, the surface gravity is determined by requiring ionization equilibrium between Fe I and Fe II. These three parameters are iterated upon until these requirements are all met. An overall [Fe/H] abundance is then calculated based on a mean of the the individual line abundances. Using this model, we synthesize a spectral region containing five Fe I lines of varying excitation potential. The only parameter that is varied is the rotational velocity. We do not deconvolve the macroturbulence from the rotational velocities, so the $v\sin i$ values listed in Tables 2, 3, 5, 7, and 9 include the effects of macroturbulence. Observing the solar spectrum and following the exact same analysis as we do for all stars in this paper enables us to compare our values to solar in a straightforward manner. This approach removes the possible systematics that may arise from this instrument, and thus we present absolute [Fe/H] (with errors $\sim$0.08 dex) values independent of the value of $\log\epsilon({\rm Fe})_\odot$. Our solar spectrum was taken of the asteroid Iris, as it closely resembles starlight through the combination of the telescope and the instrument. The final stellar parameters are listed in Tables 4, 6, 8, and 10.

## 5. Results

### 5.1. $\beta$ Pic Moving Group

We included the $\beta$ Pic members as a demonstration of the limiting factor of radial velocity measurements on the youngest stars. As seen in Table 2, the radial velocity amplitudes of these stars are quite large, 0.25-0.61 km s$^{-1}$. The observed amplitudes are within the predicted values except for three stars. GJ 803, GJ 3305 and HIP 88399 have $\Delta V_H$ magnitudes well below that of other members. For GJ 803, ground based photometry produced $\Delta V = 0.22$ (Custipoto 1998). This value would bring $A_{pred}$ to 0.41 km s$^{-1}$. This rectifies the discrepancy between predicted and observed amplitudes. If we assume $\Delta V_H$ to be 0.2 for HIP 88399, in line with other member's $\Delta V_H$, then $A_{obs}$ becomes 0.85 km s$^{-1}$, well in agreement with observation. GJ 3305 also has a remarkably low photometric amplitude. Because of lack of $v\sin i$ information, a comparison of $A_{pred}$ with $A_{obs}$ is not possible. If the low photometric amplitudes for GJ 3305 and HIP 88399 are indeed real, this would suggest that the stellar inclinations were almost pole-on. But, at least for the case of HIP 88399, the rotational velocity indicates otherwise. So, it is probable that the photometry is not accurate. Four of the stars in our survey: GJ 803, HIP 23309, HIP 29964, and HIP 76629 have been surveyed with adaptive optics by Neuhäuser et al. (2003) and were shown to harbor no distant binary companions. Thus, we can rule out brown dwarf companions and stellar companions in very close obrits as well as in several AU orbits.

### 5.2. IC 2391

Solar analogs in the IC 2391 cluster will have just arrived on the main sequence and are thus an important sample of stars for multiplicity studies. The X-ray levels of stars in this cluster confirm the age of 30 Myr (Marino et al. 2005) and the rotation of members is also consistent with that age. Despite its youth, IC 2391 has fairly low activity levels as measured by photometric variability. This is likely caused by somewhat uniform

coverage of starspots. Thus, the radial velocity variations caused by photospheric activity are also lessened. As a result, there seems to be a division in the accessibility of planet and brown dwarf detection via the radial velocity method between the ages of $\beta$ Pic and IC 2391. Members of IC 2391 are good candidates for longer term follow up (i.e. for substelar mass companions in orbits of a few weeks - months). The observed radial velocities (Table 3) agree to within error of the expected amplitude, and companions of mass >1-2 $M_{Jup}$ with orbital periods less than 6 days can be ruled out.

The stellar parameters for observed IC 2391 members are listed in Table 4. The average [Fe/H] of IC 2391 is -0.01 $\pm$ 0.12. We note, however, that BD+01 2063 is much lower in abundance than the remaining cluster members with an [Fe/H] of -0.24. If this star is truly a member of IC 2391, as indicated by the positive results of the two membership tests Montes et al. (2001) performed, then further studies into the depletion of metals in this star are warranted. However, it is more likely that this star is an interloper whose stellar history is vastly different than the surrounding cluster. Removing BD+01 2063 from the group results in a mean [Fe/H] = 0.03.

### 5.3. Castor Moving Group

The members of the Castor moving group we surveyed also show remarkable photometric stability and thus stability in the radial velocity measurements. Despite their youth, stars in the Castor group, like IC 2391, are good candidates for more precise and longer-term radial velocity searches. None of the members of the Castor moving group show radial velocity variability indicative of short-period companions (Table 5) and companions as low as 1 $M_{Jup}$ with short-periods are not detected. We measure a mean [Fe/H] of Castor members of 0.00$\pm$0.04. While our sample (5 stars) is small, there is very little scatter in the abundances.

### 5.4. Ursa Majoris Moving Group

As for the previous groups, there are no stars whose $A_{obs}$ significantly exceeds $A_{pred}$. As a result, companions with mass >1-2 $M_{Jup}$ in close-orbits are ruled out. The previously measured [Fe/H] of this association is between -0.05 and -0.09 (§2). We determine an [Fe/H] of 0.06$\pm$0.11. We attribute the difference between our measurement and previous measurements to the samples of stars chosen for each survey. There is a scatter in the abundances of "members" of 0.42 dex ($\sigma$ = 0.11 dex). We assume (perhaps incorrectly?) that these stars were formed from homogeneous material. The spread of [Fe/H] of these stars is not easily explained for a common group, i.e. scatter in the Hyades is $\pm$0.04 dex (Paulson et al. 2003, [Fe/H] = 0.13) and in the younger Pleiades $\pm$0.05 (King et al. 2000, [Fe/H] = 0.06). Four of the stars we include have abundances which are >0.10 dex higher (or lower) than the cluster median- BD+19 2531, HD 64942, HD 88654 and HD 131156A. The membership of these stars to the Ursa Majoris association, their overall metallicities and the overall abundance variations throughout the entire association should be explored further.

### 5.5. Other Nearby Young Stars

Some of the stars we include here have confirmed binary companions as noted in the literature, though our data indicate that none of them have high mass short-period orbiting companions (stellar or substellar). Those stellar companions cited in the literature include only distant companions whose radial velocity effects would be immeasurable in our data. Balega et al. (2002) found a companion to HD 15013 with a separation of 127 mas. Gaidos (1998) indicate HD 96064 has a probable M dwarf companion at 270 AU. Lowrance et al. (2005) find that HD 82443 has a binary companion at a distance of 6.86". The only star with large $A_{obs}$ is HD 82558 which has a $v$sin$i$ =28.0 km s$^{-1}$ (Kovári et al. 2004). The $v$sin$i$ is reflected in $A_{pred}$ and is much greater than $A_{obs}$. None of these stars has a companion with mass >1-2 $M_{Jup}$ in a close orbit.

## 6. Discussion

We present in this paper an initial search of young stars at different ages for substellar mass companions as well as a census of stellar parameters and metallicity. While no companions are detected in this sample, we list mass limits for rejected planets and brown dwarfs. Stars of age ~IC 2391 and older are suitable for long-term ra-

dial velocity surveys for high-mass, short-period (∼few months) companions based on their relatively stable activity levels. For younger stars, like $\beta$ Pic members, we are limited to searches for short-period brown dwarf companions. For these stars, the velocity technique employing telluric lines as a velocity reference is sufficient. The sub-5 m s$^{-1}$ precision gained through use of an $I_2$ cell provides little improvement to a star whose intrinsic activity levels are greater than 0.05 km s$^{-1}$. Thus, for longer-term follow-up of stars in our paper, velocity precision of 5-10 m s$^{-1}$ is more than adequate.

With sufficient telescope allocation, it is possible to look for longer period planetary mass companions using the radial velocity technique. In order to do so, one could average the velocity over the course of a rotation cycle, as the velocity amplitude will be (or at least come close to) zero. Of course, small variations in total spot coverage may cause "zero point" offsets, but this technique should be able to allow for detection of companions in orbits of a few weeks-months. Unfortunately, this type of project would be considerably less efficient than the current radial velocity planet searches by lowering the number of stars that could be surveyed.

The lack of "hot Jupiters" in this sample is not surprising. Only 0.8% of stars have such objects within 0.1 AU of the parent star (Marcy et al. 2005). Our sample is considerably smaller than what would be required to have a meaningful statistic. However, we can state that the incidence of such objects around young stars is less than 1.5% and likely much smaller, in agreement with the 0.8% incidence of companions around old stars. To build better statistics, a comprehensive and dedicated survey similar to the N2K project (e.g., Fischer et al. 2005) should be carried out for the youngest nearby stars.

We further recommend combining radial velocity surveys for close-in companions with imaging surveys for distant companions. The radial velocity technique is limited to detection of only high-mass close-in companions, whereas AO and other imaging techniques are only sensitive to more distant, young, high-mass companions. Combining these types of surveys on the same set of young stars is the best way to begin to understand the evolution and formation of planets and brown dwarfs at these young and intermediate ages.

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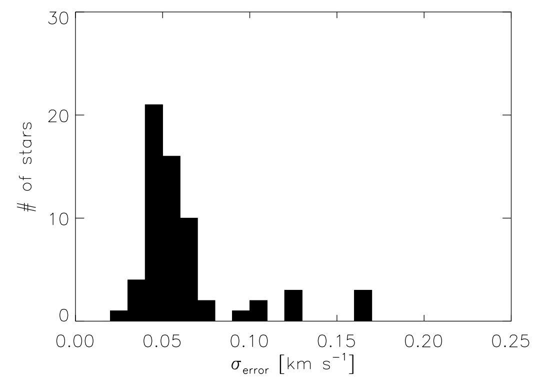


Fig. 1.— A histogram of the mean error for each star. Each component of this histogram is the rms of the errors from all observations of a given star.

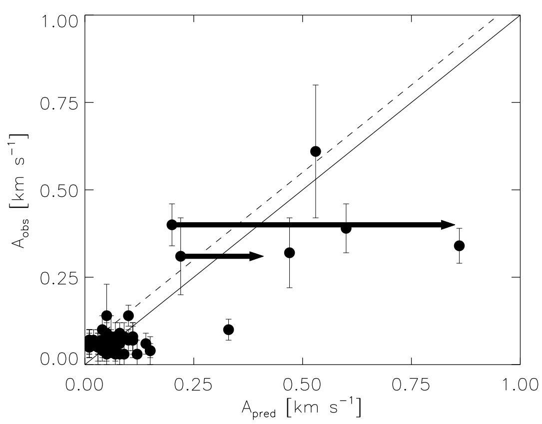


Fig. 2.— Observed versus predicted radial velocity amplitudes. Arrows shown correspond to the two stars in $\beta$ Pic which have questionable photometry, as discussed in the text. A (*solid*) 1:1 line is drawn along with a (*dashed*) line corresponding to the mean error of all data.

Table 1
Observing Log

| Dates | MIKE Red Range [Å] | MIKE Blue Range [Å] |
|---|---|---|
| October 2 - 5, 2003 | 4500 - 7100 | 3700 - 4800 |
| December 9 - 10, 2003 | 4500 - 7100 | 3700 - 4800 |
| March 10 - 13, 2004 | 4750 - 8500 | 3700 - 4800 |
| April 2 - 5, 2004 | 4750 - 8500 | 3700 - 4800 |
| June 1 - 3, 2004 | 4900 - 8900 | 3700 - 4800 |
| July 15 - 19, 2004 | 4900 - 8900 | 3700 - 4800 |
| March 20 - 21, 2005 | 4900 - 8900 | 3700 - 4800 |

Table 2
$\beta$ Pic Moving Group Velocities

| Star | # nights obs | # obs | $v\sin i$ [km s$^{-1}$] | $\Delta V_H$ [mag] | $A_{pred}$ [km s$^{-1}$] | $A_{obs}$ [km s$^{-1}$] | $\sigma_{\rm error}$ [km s$^{-1}$] | $M_{3\sigma}$ [$M_{Jup}$] | Notes |
|---|---|---|---|---|---|---|---|---|---|
| GJ 803 | 8 | 13 | (9) | 0.11 | 0.22 | 0.31 | 0.16 | ··· | 1,2 |
| GJ 3305 | 5 | 11 | ··· | 0.02 | ··· | 0.25 | 0.12 | ··· | 1 |
| HIP 23309 | 13 | 23 | (11) | 0.20 | 0.47 | 0.32 | 0.16 | 9 | 1 |
| HIP 29964 | 16 | 25 | (13) | 0.22 | 0.60 | 0.39 | 0.12 | 11 | 1 |
| HIP 76629 | 14 | 35 | (11) | 0.23 | 0.53 | 0.61 | 0.36 | 8 | 1 |
| HIP 88399 | 7 | 16 | (20) | 0.04 | 0.20 | 0.40 | 0.10 | ··· | 1,3 |

(1) Adopted $v\sin i$ values from Zuckerman et al. (2001). (2) Cutispoto (1998) give $\Delta$V=0.22. Adopting this value would give a predicted amplitude of 0.414. (3) If we adopt an average photometric amplitude of 0.2 (typical for this association) instead, the predicted amplitude becomes 0.845 km s$^{-1}$.

Table 3
IC 2391 Radial Velocities

| Star | # nights obs | # obs | $v\sin i$ [km s$^{-1}$] | $\Delta V_H$ [mag] | $A_{pred}$ [km s$^{-1}$] | $A_{obs}$ [km s$^{-1}$] | $\sigma_{\rm error}$ [km s$^{-1}$] | $M_{3\sigma}$ [$M_{Jup}$] | Notes |
|---|---|---|---|---|---|---|---|---|---|
| BD+01 2063 | 7 | 14 | 4.0 | 0.05 | 0.05 | 0.03 | 0.02 | 1 | |
| HD 111813 | 3 | 4 | 3.8 | 0.08 | 0.07 | 0.05 | 0.06 | 1 | |
| HD 118100 | 4 | 10 | (14.0) | 0.15 | 0.33 | 0.10 | 0.04 | 2 | 1 |
| HD 120352 | 4 | 9 | 3.2 | 0.05 | 0.04 | 0.06 | 0.04 | 1 | |
| HD 140913 | 1 | 3 | 9.0 | 0.07 | 0.15 | 0.04 | 0.03 | 2 | |
| HD 142072 | 3 | 8 | 6.1 | 0.05 | 0.07 | 0.08 | 0.06 | 1 | |
| HD 157750 | 4 | 8 | 3.4 | 0.05 | 0.04 | 0.07 | 0.05 | 1 | |
| HD 209779 | 2 | 7 | 6.8 | 0.04 | 0.07 | 0.03 | 0.06 | 1 | |

(1) $v\sin i$ from Cutispoto et al. (2002)

Table 4
IC 2391 Stellar Parameters

| Star | $T_{\rm eff}$ [K] | $\log g$ [cm s$^{-2}$] | $\xi$ [km s$^{-1}$] | [Fe/H] |
|---|---|---|---|---|
| BD+01 2063 | 5350 | 4.5 | 0.8 | -0.24 |
| HD 111813 | 5000 | 4.6 | 0.8 | -0.08 |
| HD 118100 | ··· | ··· | ··· | ··· |
| HD 120352 | 5500 | 4.5 | 0.8 | -0.03 |
| HD 140913 | 6050 | 4.4 | 0.8 | 0.06 |
| HD 142072 | 5900 | 4.4 | 0.8 | 0.11 |
| HD 157750 | 5850 | 4.4 | 0.5 | 0.10 |
| HD 209779 | 5850 | 4.4 | 0.5 | 0.04 |

Table 5
Castor Moving Group Radial Velocities

| Star | # nights obs | # obs | $v$sin$i$ [km s$^{-1}$] | $\Delta$V$_H$ [mag] | $A_{pred}$ [km s$^{-1}$] | $A_{obs}$ [km s$^{-1}$] | $\sigma_{\rm error}$ [km s$^{-1}$] | M$_{3\sigma}$ [M$_{Jup}$] | Notes |
|---|---|---|---|---|---|---|---|---|---|
| BD+24 2700 | 4 | 8 | 2.0 | 0.06 | 0.03 | 0.06 | 0.05 | 1 | |
| HD 41842 | 10 | 22 | 3.0 | 0.08 | 0.06 | 0.05 | 0.04 | 1 | |
| HD 77825 | 5 | 10 | 2.5 | 0.07 | 0.04 | 0.07 | 0.04 | 1 | |
| HD 94765 | 6 | 11 | 2.0 | 0.07 | 0.03 | 0.05 | 0.03 | 1 | |
| HD 103720 | 5 | 9 | · · · | 0.08 | · · · | 0.07 | 0.04 | 1 | |
| HD 181321 | 3 | 8 | 14.0 | 0.04 | 0.14 | 0.06 | 0.04 | 2 | |
| HD 216803 | 3 | 7 | (3.0) | 0.04 | 0.03 | 0.05 | 0.05 | 1 | 1 |

(1) $v$sin$i$ from Nordström et al. (2004)

Table 6
Castor Moving Group Stellar Parameters

| Star | $T_{\rm eff}$ [K] | log$g$ [cm s$^{-2}$] | $\xi$ [km s$^{-1}$] | [Fe/H] |
|---|---|---|---|---|
| BD+24 2700 | 5100 | 4.6 | 0.8 | 0.02 |
| HD 41842 | 5150 | 4.5 | 1.0 | -0.03 |
| HD 77825 | 5100 | 4.5 | 1.0 | -0.05 |
| HD 94765 | 5050 | 4.5 | 0.8 | 0.03 |
| HD 103720 | · · · | · · · | · · · | · · · |
| HD 181321 | 6000 | 4.5 | 1.0 | 0.04 |
| HD 216803 | · · · | · · · | · · · | · · · |

Table 7
Ursa Majoris Moving Group Radial Velocities

| Star | # nights obs | # obs | $v$sin$i$ [km s$^{-1}$] | $\Delta$V$_H$ [mag] | $A_{pred}$ [km s$^{-1}$] | $A_{obs}$ [km s$^{-1}$] | $\sigma_{\rm error}$ [km s$^{-1}$] | M$_{3\sigma}$ [M$_{Jup}$] |
|---|---|---|---|---|---|---|---|---|
| BD+19 2531 | 6 | 8 | 1.5 | 0.02 | 0.01 | 0.06 | 0.04 | 1 |
| HD 26913 | 13 | 23 | 8.5 | 0.04 | 0.08 | 0.09 | 0.04 | 2 |
| HD 38392 | 9 | 16 | 1.0 | 0.05 | 0.01 | 0.07 | 0.04 | 2 |
| HD 41593 | 4 | 6 | 3.8 | 0.10 | 0.09 | 0.03 | 0.06 | 1 |
| HD 60491 | 5 | 13 | 5.4 | 0.06 | 0.08 | 0.06 | 0.04 | 1 |
| HD 61606 | 11 | 25 | 2.2 | 0.05 | 0.03 | 0.05 | 0.07 | 1 |
| HD 64942 | 12 | 28 | 8.5 | 0.05 | 0.10 | 0.07 | 0.05 | 2 |
| HD 81659 | 8 | 19 | 1.0 | 0.06 | 0.01 | 0.05 | 0.03 | 1 |
| HD 88654 | 6 | 17 | · · · | 0.03 | · · · | 0.04 | 0.04 | · · · |
| HD 98712 | 11 | 21 | 4.5 | 0.04 | 0.05 | 0.09 | 0.05 | 2 |
| HD 131156A | 4 | 9 | 3.7 | 0.04 | 0.04 | 0.10 | 0.05 | 1 |
| HD 165185 | 4 | 8 | 7.7 | 0.05 | 0.09 | 0.08 | 0.06 | 1 |

Table 8

Ursa Majoris Moving Group Stellar Parameters

| Star | $T_{\rm eff}$ [K] | log$g$ [cm s$^{-2}$] | $\xi$ [km s$^{-1}$] | [Fe/H] |
|---|---|---|---|---|
| BD+19 2531 | 5100 | 4.5 | 0.6 | 0.18 |
| HD 26913 | 5600 | 4.5 | 0.6 | 0.05 |
| HD 38392 | 5250 | 4.5 | 1.0 | 0.04 |
| HD 41593 | 5350 | 4.5 | 0.8 | 0.10 |
| HD 60491 | 5300 | 4.5 | 1.0 | -0.06 |
| HD 61606 | 5200 | 4.5 | 0.8 | 0.03 |
| HD 64942 | 5800 | 4.4 | 0.7 | 0.14 |
| HD 81659 | 5700 | 4.4 | 0.6 | 0.10 |
| HD 88654 | 5600 | 4.5 | 1.0 | 0.25 |
| HD 98712 | 5450 | 4.5 | 1.7 | 0.04 |
| HD 131156A | 5550 | 4.5 | 0.7 | -0.17 |
| HD 165185 | 5900 | 4.4 | 0.7 | 0.07 |

Table 9

Other Nearby Young Stars Radial Velocities

| Star | # nights obs | # obs | $v$sin$i$ [km s$^{-1}$] | $\Delta$V$_H$ [mag] | $A_{pred}$ [km s$^{-1}$] | $A_{obs}$ [km s$^{-1}$] | $\sigma_{\rm error}$ [km s$^{-1}$] | M$_{3\sigma}$ [M$_{Jup}$] | Notes |
|---|---|---|---|---|---|---|---|---|---|
| HD 10008 | 2 | 5 | 1.0 | 0.05 | 0.01 | 0.06 | 0.05 | 1 | |
| HD 15013 | 2 | 4 | 9.3 | 0.05 | 0.11 | 0.07 | 0.07 | 1 | |
| HD 17925 | 6 | 14 | 4.2 | 0.04 | 0.04 | 0.04 | 0.04 | 1 | |
| HD 19668 | 2 | 5 | 7.0 | 0.07 | 0.12 | 0.03 | 0.05 | 1 | |
| HD 82443 | 6 | 7 | 5.2 | 0.09 | 0.11 | 0.08 | 0.06 | 2 | |
| HD 82558 | 8 | 23 | (28.0) | 0.14 | 0.86 | 0.34 | 0.09 | 8 | 1 |
| HD 85512 | 8 | 14 | ··· | 0.04 | ··· | 0.12 | 0.06 | ··· | |
| HD 91901 | 8 | 16 | 1.0 | 0.06 | 0.01 | 0.05 | 0.04 | 1 | |
| HD 92945 | 4 | 10 | 5.7 | 0.06 | 0.08 | 0.03 | 0.04 | 1 | |
| HD 96064 | 6 | 15 | 5.4 | 0.09 | 0.11 | 0.07 | 0.06 | 2 | |
| HD 102195 | 11 | 17 | 3.5 | 0.05 | 0.04 | 0.06 | 0.04 | 2 | |
| HD 108767B | 3 | 10 | 1.8 | ··· | ··· | 0.06 | 0.04 | ··· | |
| HD 110514 | 5 | 7 | 4.9 | 0.04 | 0.05 | 0.04 | 0.06 | 1 | |
| HD 113449 | 8 | 15 | 5.8 | 0.07 | 0.10 | 0.14 | 0.05 | 2 | |
| HD 124106 | 4 | 11 | 3.8 | 0.04 | 0.04 | 0.05 | 0.04 | 1 | |
| HD 130004 | 6 | 11 | 1.0 | 0.07 | 0.02 | 0.07 | 0.04 | 1 | |
| HD 130307 | 3 | 6 | 1.0 | 0.05 | 0.01 | 0.07 | 0.04 | 1 | |
| HD 140901 | 4 | 9 | 1.6 | 0.03 | 0.01 | 0.05 | 0.05 | 1 | |
| HD 149661 | 8 | 18 | 2.1 | 0.02 | 0.01 | 0.07 | 0.04 | 1 | |
| HD 166348 | 4 | 7 | ··· | 0.06 | ··· | 0.05 | 0.03 | ··· | |
| HD 180134 | 3 | 9 | 8.1 | 0.03 | 0.06 | 0.07 | 0.04 | 1 | |
| HD 184985 | 3 | 8 | ··· | 0.02 | ··· | 0.08 | 0.05 | ··· | |
| HD 186803 | 3 | 6 | ··· | 0.04 | ··· | 0.04 | 0.05 | ··· | |
| HD 187101 | 2 | 5 | 10.5 | 0.06 | 0.15 | 0.04 | 0.06 | 1 | |
| HIP 51317 | 8 | 13 | (<3.0) | 0.08 | 0.06 | 0.08 | 0.10 | 2 | 2 |
| HIP 60661 | 12 | 16 | ··· | 0.10 | ··· | 0.13 | 0.05 | ··· | |
| HIP 67092 | 11 | 16 | ··· | 0.11 | ··· | 0.10 | 0.12 | ··· | |
| HIP 74995 | 8 | 13 | (<2.1) | 0.11 | 0.05 | 0.14 | 0.16 | 2 | 2 |

(1) $v$sin$i$ from Kovári et al. (2004) (2) $v$sin$i$ from Delfosse et al. (1998)

Table 10
Other Young Stars Stellar Parameters

| Star | $T_{\rm eff}$ [K] | log$g$ [cm s$^{-2}$] | $\xi$ [km s$^{-1}$] | [Fe/H] |
|---|---|---|---|---|
| HD 10008 | 5350 | 4.5 | 0.8 | -0.08 |
| HD 15013 | 5350 | 4.5 | 0.9 | -0.11 |
| HD 17925 | 5600 | 4.5 | 0.7 | 0.08 |
| HD 19668 | 5500 | 4.5 | 0.9 | -0.04 |
| HD 82443 | 5300 | 4.5 | 0.8 | -0.12 |
| HD 82558 | ... | ... | ... | ... |
| HD 85512 | ... | ... | ... | ... |
| HD 91901 | 5200 | 4.6 | 0.8 | -0.04 |
| HD 92945 | 5200 | 4.5 | 0.9 | 0.03 |
| HD 96064 | 5400 | 4.5 | 0.7 | 0.02 |
| HD 102195 | 5300 | 4.5 | 0.6 | 0.03 |
| HD 108767B | 5100 | 4.6 | 0.8 | -0.01 |
| HD 110514 | 5400 | 4.5 | 0.8 | -0.03 |
| HD 113449 | 5350 | 4.5 | 0.5 | -0.03 |
| HD 124106 | 5150 | 4.5 | 0.6 | -0.17 |
| HD 130004 | 5250 | 4.6 | 0.9 | -0.24 |
| HD 130307 | 5100 | 4.5 | 0.9 | -0.21 |
| HD 140901 | 5600 | 4.5 | 0.8 | 0.01 |
| HD 149661 | 5250 | 4.5 | 0.9 | -0.01 |
| HD 166348 | ... | ... | ... | ... |
| HD 180134 | 6500 | 4.2 | 0.8 | -0.20 |
| HD 184985 | ... | ... | ... | ... |
| HD 186803 | ... | ... | ... | ... |
| HD 187101 | 6000 | 4.4 | 0.9 | 0.04 |
| HIP 51317 | ... | ... | ... | ... |
| HIP 60661 | ... | ... | ... | ... |
| HIP 67092 | ... | ... | ... | ... |
| HIP 74995 | ... | ... | ... | ... |